

## TES carbon monoxide validation with DACOM aircraft measurements during INTEX-B 2006

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[1] Validation of Tropospheric Emission Spectrometer (TES) tropospheric CO profiles with in situ CO measurements from the Differential Absorption CO Measurement (DACOM) instrument during the Intercontinental Chemical Transport Experiment (INTEX)-B campaigns in March to May 2006 are presented. For each identified DACOM CO profile, one to three TES CO profiles are selected closest in location to the small area that the DACOM profile covers. The time differences between the comparison profiles are within 2 hours. The DACOM CO vertical profiles are adjusted by applying nearest coincident TES averaging kernels and the a priori profiles. This step accounts for the effect of the vertical resolution of the TES CO retrievals and removes the influence of the a priori assumptions in the comparisons. Comparison statistics for data taken near Houston in March 2006 show good agreement between TES and the adjusted DACOM CO profiles in the lower and middle troposphere with a correlation coefficient of 0.87. On average, the TES CO volume mixing ratio profile is 0–10% lower than the adjusted DACOM CO profile from the lower to middle troposphere. This is within the 10–20% standard deviations of the TES or DACOM CO profiles taken in the Houston area. The comparisons of TES and DACOM CO profiles near Hawaii and Anchorage in April to May 2006 are not as good. In these regions the aircraft DACOM CO profiles are characterized by plumes or enhanced CO layers, consistent with known features in the tracer fields due to transpacific transport of polluted air parcels originating from East Asia. Although TES observations over the Pacific region also show localized regions of enhanced CO, the coincidence criteria for obtaining good comparisons with aircraft measurements are challenging. The meaning of validation comparisons in profile portions where TES retrievals have little sensitivity is addressed. Examinations of characteristic parameters in TES retrievals are important in data applications.

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### 1. Introduction

[2] The Tropospheric Emission Spectrometer (TES) instrument on the NASA Aura satellite has been making nadir measurements of the Earth infrared spectral radiance since September 2004 [Beer *et al.*, 2001; Beer, 2006]. TES retrievals of co-located tropospheric ozone and CO profiles

from the radiance measurements are key products for studies of ozone chemistry and transport in the troposphere. Validation efforts for TES ozone and CO profiles have been documented and updated via the TES Validation Report [Osterman *et al.*, 2006] and publications [e.g., Worden *et al.*, 2007; Nassar *et al.*, 2007]. In addition, Rinsland *et al.* [2006] presented the historical trends of the TES instrument performance and the associated trends for the sensitivities in TES-retrieved CO profiles. Luo *et al.* [2007] presented comparisons of TES CO retrievals and those from MOPITT and addressed the issues of proper comparisons between remote sensing retrievals. Several aircraft campaigns have been conducted that have produced data for Aura instrument validation, e.g., AVE (Aura Validation Experiment) near Houston in October to November 2004, Costa Rica AVE in January to February 2006, and Intercontinental Chemical Transport Experiment (INTEX)-B in March to May 2006 near Houston, TX, Hawaii, HI, and Anchorage, AK. This paper describes the TES CO validations using in situ CO

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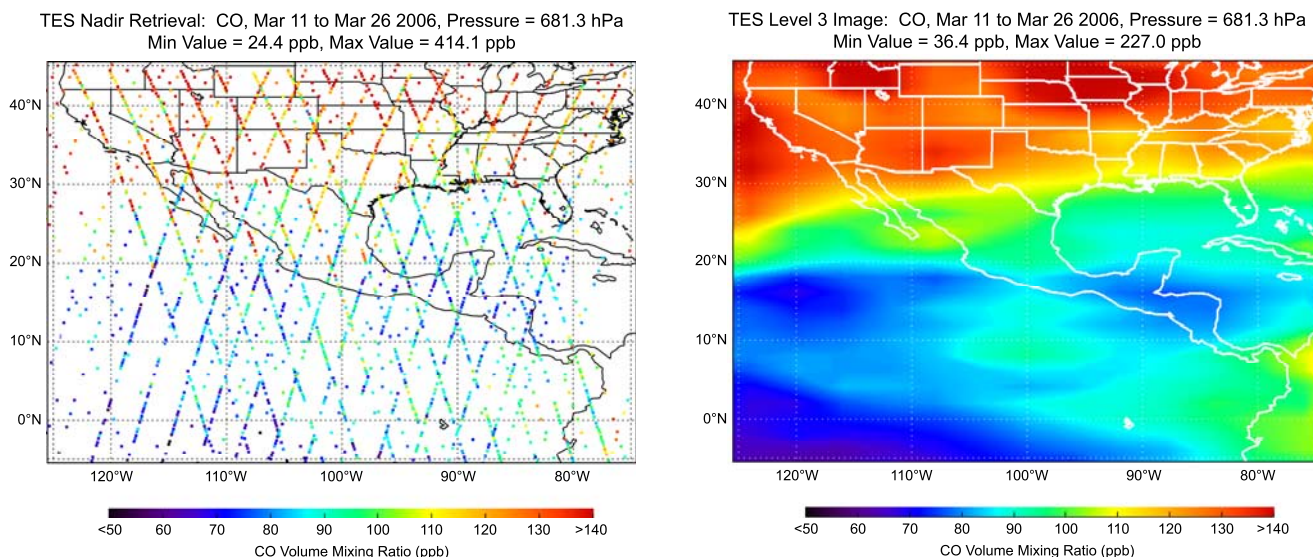
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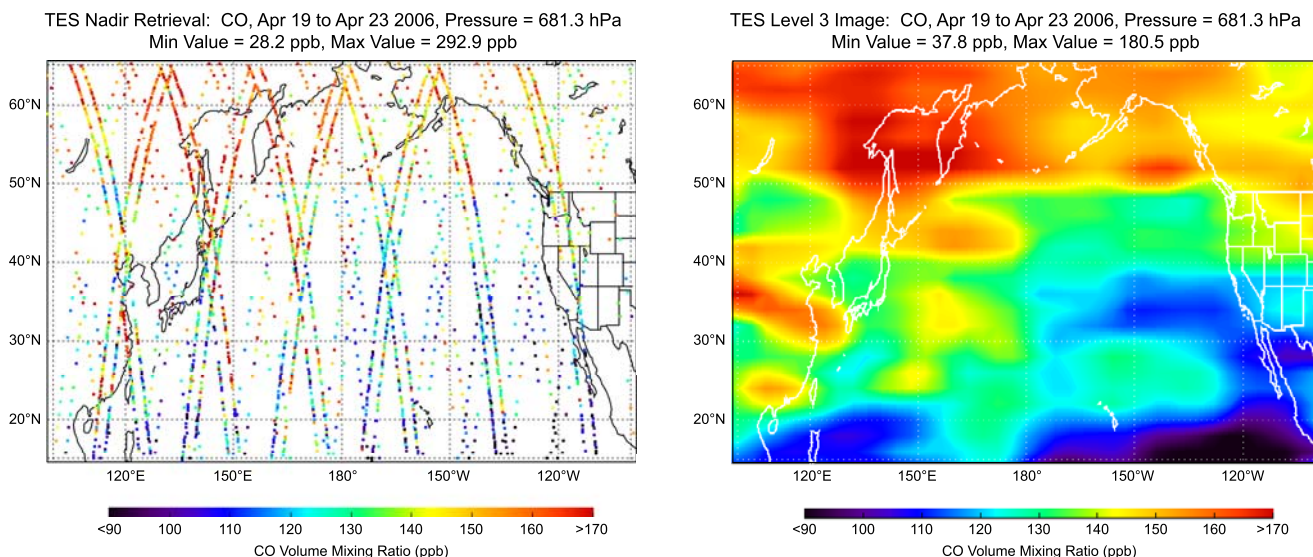


**Figure 1.** TES Global Survey and Step & Stare observations of CO near Houston, 11–26 March 2006. The pressure level plotted is 681.3 hPa. The left panel shows the enlarged footprints (size of the real footprint is 8.3X5.3 km). The right panel shows the bin-averaged image with the bin size of 6° longitude X 1.6° latitude.

measurements by the Differential Absorption CO Measurement (DACOM) instrument [Sachse *et al.*, 1987] on the DC-8 aircraft during the INTEX-B campaign (<http://www.espo.nasa.gov/intex-b/>). The validation of TES CO data using measurements from the AVE campaigns is presented by J. Lopez *et al.* (TES carbon monoxide validation during two AVE campaigns using the Argus and ALIAS instruments on NASA's WB-57F, submitted to *Journal of Geophysical Research*, 2007; hereinafter referred to as Lopez *et al.*, submitted manuscript, 2007).

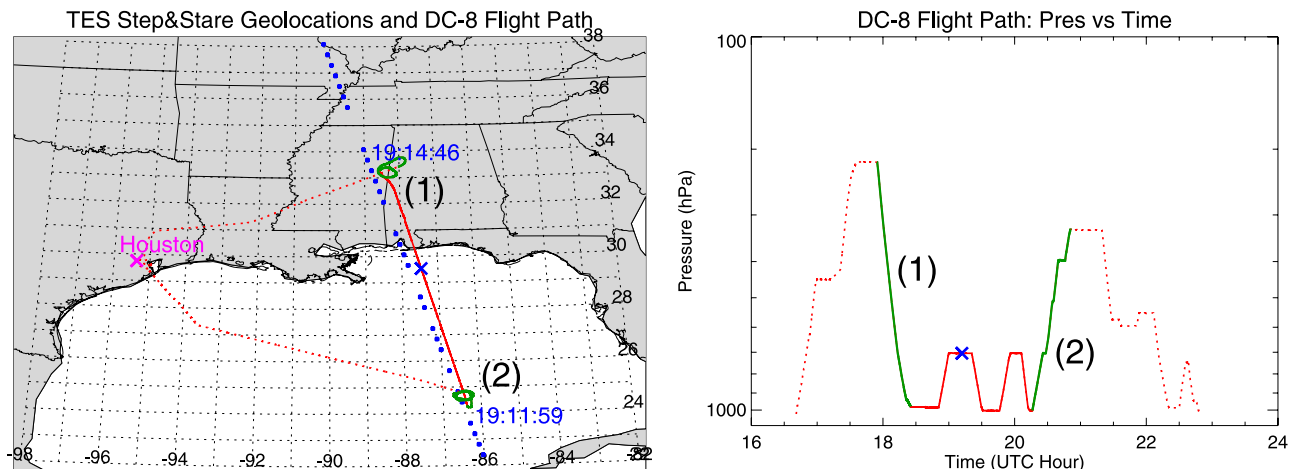
[3] Aircraft in situ measurements of atmospheric specie concentrations can be useful in validating retrievals from the satellite remote sensing measurements [e.g., Emmons *et al.*,

2004]. However, there are some challenges in performing these comparisons. First, only a very limited number of comparison pairs can be obtained over coincident pressure ranges, locations and times. As a tracer of atmospheric transport with a lifetime of weeks [Logan *et al.*, 1981], the CO distribution has distinct characteristics associated with sources and meteorological conditions in different areas. It is therefore difficult to fully address possible systematic biases in the two measurement sets. The second difficulty is that in the process of proper comparison, the in situ high vertical resolution measurements need to be adjusted by the remote sensing observation operators including a priori assumptions used in the satellite data retrievals. As clouds



**Figure 2.** TES Global Survey and Step & Stare observations of CO over Pacific Ocean, 19–23 April 2006. Plotting methodology is identical to Figure 1.

### DC-8 Flight Path and TES Step&Stare Geolocations: Mar-04-2006



**Figure 3.** Left panel shows DC-8 flight path (red) and TES Step & Stare geolocations (blue dots) for 4 March 2006 near Houston. The right panel shows the DC-8 flight path in pressure as a function of UTC time. The blue cross symbols are where and when DC-8 and TES coincide in time, and the green lines represent the two selected DC-8 vertical spirals through the atmosphere. The DACOM CO measurements taken in these two spiral profiles are used for TES validation.

are common in the troposphere, their presence is also an important factor to consider when comparing space-based measurements with in situ measurements. Validation comparisons are therefore only performed for satellite retrievals sensitive to the nadir radiance measurements. In low sensitivity cases where a priori dominates the retrieval profiles, the comparison is meaningless. We illustrate the above points with TES CO data validation in the three phases of the INTEX-B campaign.

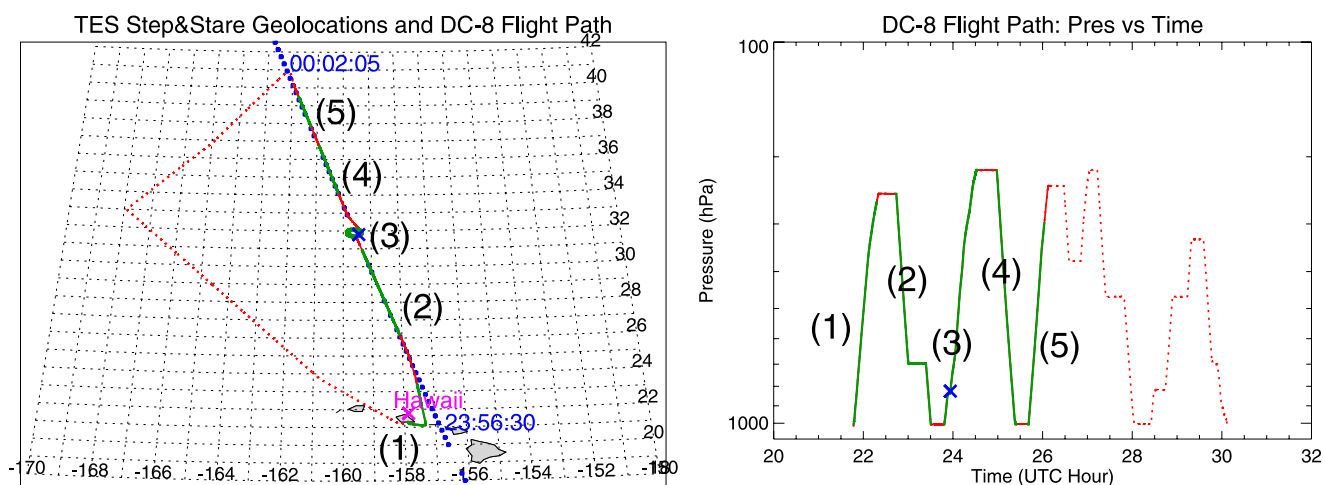
[4] TES nadir retrievals of CO in the middle to upper troposphere are compared with retrievals from limb measurements made with MLS (Microwave Limb Sounder) instruments [Livesey *et al.*, 2007]. TES CO validation using

the Argus and Alias in situ measurements in the AVE campaigns and the comparisons between the two in situ results are documented in a separate paper (Lopez *et al.*, submitted manuscript, 2007). We will discuss future TES CO validation activities with larger data sets at the conclusion of this paper.

### 2. TES and DACOM Observations of CO During INTEX-B 2006

[5] During INTEX-B 2006, TES made routine Global Survey (GS) measurements every other day, and scheduled Step & Stare (SS) special observations in the GS “off” days

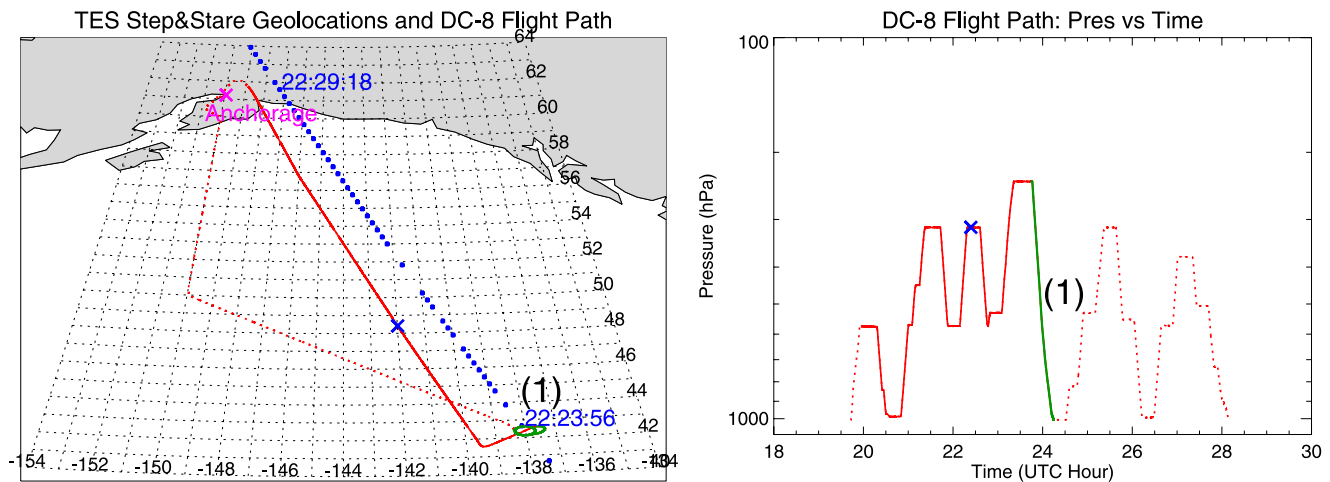
### DC-8 Flight Path and TES Step&Stare Geolocations: Apr-23-2006



**Figure 4.** DC-8 flight path and TES Step & Stare geolocations for 23 April 2006 near Hawaii. All symbols and colored lines are the same as those in Figure 3. The DACOM CO measurements taken in the four spiral and one departure profiles are used for TES validation.



## DC-8 Flight Path and TES Step&Stare Geolocations: May-09-2006



**Figure 5.** DC-8 flight path and TES Step & Stare geolocations for 9 May 2006 near Anchorage. All symbols and colored lines are the same as those in Figure 3. The DACOM CO measurements taken in the spiral profile are used for TES validation.

over the regions where the aircraft flew. TES nadir footprints are separated by  $\sim 180$  km along the Aura ground track for GS and  $\sim 45$  km for SS observations. The size of a TES nadir footprint is about  $5 \text{ km} \times 8 \text{ km}$ . Figures 1 and 2 illustrate TES measurement locations and the CO values at 681.3 hPa near Houston in 11–26 March (16 days) and over northern Pacific Ocean in 19–23 April (4 days). TES measurements of CO in both areas show day-to-day variability depending on the strength of the CO sources, the meteorological conditions, and the TES measurement locations and times. In general, the CO distributions in the three INTEX-B areas show different characteristics. For example, compared to the Houston area, CO values near Hawaii and Anchorage show larger variations in the middle or upper troposphere associated with episodes of transpacific transport of polluted air.

[6] This paper uses TES Version 003 data that have been recently processed and were available for only a few TES observation days at the time of this paper was written. The major difference between V003 and V002 for the TES CO retrievals is the increased variability at high latitudes due to a relaxation of the retrieval constraint.

[7] For TES CO validation, we group the DACOM CO measurements into three groups: Houston, Hawaii, and Anchorage. During the INTEX-B campaign, the flight planning teams made efforts to schedule parts of the aircraft flight path along a portion of the Aura ground track with the aircrafts flew both ascending and descending spirals near TES footprints to optimize the profile samplings for validation of the TES profiles. Figures 3, 4, and 5 illustrate the DC-8 flight paths and the TES nadir measurement locations for three days during the INTEX-B campaign. Vertical profiles are identified for each flight in the figures. The flight path for each day is unique and details can be found on the INTEX-B Web site (<http://www.espo.nasa.gov/intex-b/>). During these flights there were 9 DC-8 profiles near Houston, 13 profiles near Hawaii, and 3 profiles

near Anchorage which can be used for TES and DACOM CO comparisons.

[8] Tables 1, 2, and 3 provide more detail about the TES-DACOM comparisons. Up to three TES profiles are selected close in location to each DACOM profile. For each comparison the distance and the time between TES and DACOM profiles are recorded. Most comparisons are within two hours and 100 km.

[9] TES CO retrievals have been described previously by Rinsland *et al.* [2006] and Luo *et al.* [2007]. In particular, the vertical resolution of the CO retrievals and the influence of the a priori assumptions on the retrievals are characterized by the degrees of freedom for signal (DOF). In cases where clouds were in the field of view, TES CO retrievals under the clouds are dominated by the a priori. As illustrated in the next section, the TES CO averaging kernel describes the vertical extent to which the true CO profile contributes to each of the retrieved values. Tables 1–3 also list DOFs and the effective cloud optical depths (OD) [Kulawik *et al.*, 2006] for the selected TES CO profiles paired with DACOM CO profiles. For most cases, the effective cloud OD retrieved by TES is less than 0.1, and the DOF for most cases are greater than 1.2.

[10] Many of the INTEX-B aircraft flights were scheduled to coincide with TES Step & Stare (SS) observations. Figure 6 is an example of TES CO retrievals along the Aura flight track plotted as a cross section of latitude versus pressure on 4 March 2006. The TES SS covers South America, the Caribbean Sea, the Gulf of Mexico, and extends to the north across Mississippi etc. The enhanced CO in the lower troposphere is evident over S. America (5S–10N), the Gulf of Mexico (20N–30N), and the continental United States (30N–45N). The flight path of the DC-8 is overlaid on the TES CO curtain image. It sampled a very limited portion of the atmosphere that the TES SS covered.

[11] The DACOM spectrometer system is an airborne fast-response (1 sec) high precision (1% or 1 ppbv) sensor

**Table 1.** TES and DACOM Comparison Information for INTEX-B Campaign Near Houston, 4–21 March 2006<sup>a</sup>

	4 March		9 March		11 March		12 March		16 March		19 March	
	Profile 1	Profile 2	Profile 1	Profile 2	Profile 1	Profile 2	Profile 1	Profile 2	Profile 1	Profile 2	Profile 1	Profile 2
TES Obs Type, Run ID	SS, 3399	SS, 3399	GS, 3429	GS, 3429	GS, 3437	SS, 3440	SS, 3440	SS, 3440	SS, 3459	GS, 3484	GS, 3484	SS 3496
DC-8 Flights	Flt 3	Flt 3	Flt 4	Flt 4	Flt 5	Flt 6	Flt 6	Flt 6	Flt 7	Flt 8	Flt 8	Flt 9
Distance btw TES and DACOM, km	53	25	24	20	no coincidence	16	16	16	12	43	88	no coincidence
Time btw TES and DACOM, hours	0.8–1.4	1–1.6	0.5–1.1	0–0.5	no coincidence	0.9–1.25	1–1.5	1–1.5	0–0.5	0–0.3	0.5–1.5	no coincidence
TES DOF	1.8	1.7	1.3–1.4	1.3–1.4	no coincidence	1.5	1.5	1.5	1.5	1.8	1.8	no coincidence
TES Cloud OD	<0.1	<0.1	<0.1	<0.5	no coincidence	>1.0	<0.1	<0.1	<0.1–1.0	<0.1	<0.1	no coincidence

<sup>a</sup>Total number of DACOM CO profiles for comparisons in 7 flights: 9.**Table 2.** TES and DACOM Comparison Information for INTEX-B Campaign Near Hawaii, 17 April to 1 May 2006<sup>a</sup>

	17 April		23 April		25 April		28 April		1 May	
	Profile 1	Profile 2	Profile1	Profile2	Profile3	Profile4	Profile5	Profile 1	Profile 2	Profile 3
TES Obs Type, and Run ID	SS, 3700	SS, 3700	SS, 3830	SS, 3830	SS, 3830	SS, 3830	SS, 3830	SS, 3921	SS, 3961	SS, 3961
DC-8 Flights	Flt 10 (transit) 17	Flt 10 (transit) 328	Flt 11	Flt 11	Flt 11	Flt 11	Flt 11	Flt 13	Flt 14 (transit) 18	Flt 14 (transit) 102
Distance btw TES and DACOM, km	0–0.5	0.5–1.2	1.8–2.3	0.5–1.2	0–0.5	1–1.5	1.7–2.2	2.5–3.0	0–0.3	0–0.3
Time btw TES and DACOM, hours	1.6	1.4	1.6	1.5–1.7	1.5–1.6	1.5–1.6	1.0–1.5	1.4–1.5	1.2–1.3	1.1
TES DOF	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
TES Cloud OD			and 0.7	and 1.0	and 3.0	and 0.4	and 0.4	and 0.4	and 2	and 2

<sup>a</sup>Total number of DACOM CO profiles for comparisons in 5 flights: 15.

**Table 3.** TES and DACOM Comparison Information for INTEX-B Campaign Near Anchorage, 4–15 May 2006<sup>a</sup>

	4 May	7 May	9 May	12 May	15 May
TES Obs Type, Run ID	GS	SS, 4112	SS, 4154	GS, 4211	SS, 4268
DC-8 Flights	Flt 15	Flt 16	Flt 17	Flt 18	Flt 18 (transit)
Number of DACOM profiles	no coincidence	1	1	1	no coincidence
Distance btw TES and DACOM, km	no coincidence	322	10	176	no coincidence
Time btw TES and DACOM, hours	no coincidence	1.5–2.0	1.5–2.0	0–0.5	no coincidence
TES DOF	no coincidence	1.3–1.5	1.2–1.5	1.1	no coincidence
TES Cloud OD	no coincidence	<0.1 & 0.4	<0.1 & 1.2	0.5	no coincidence

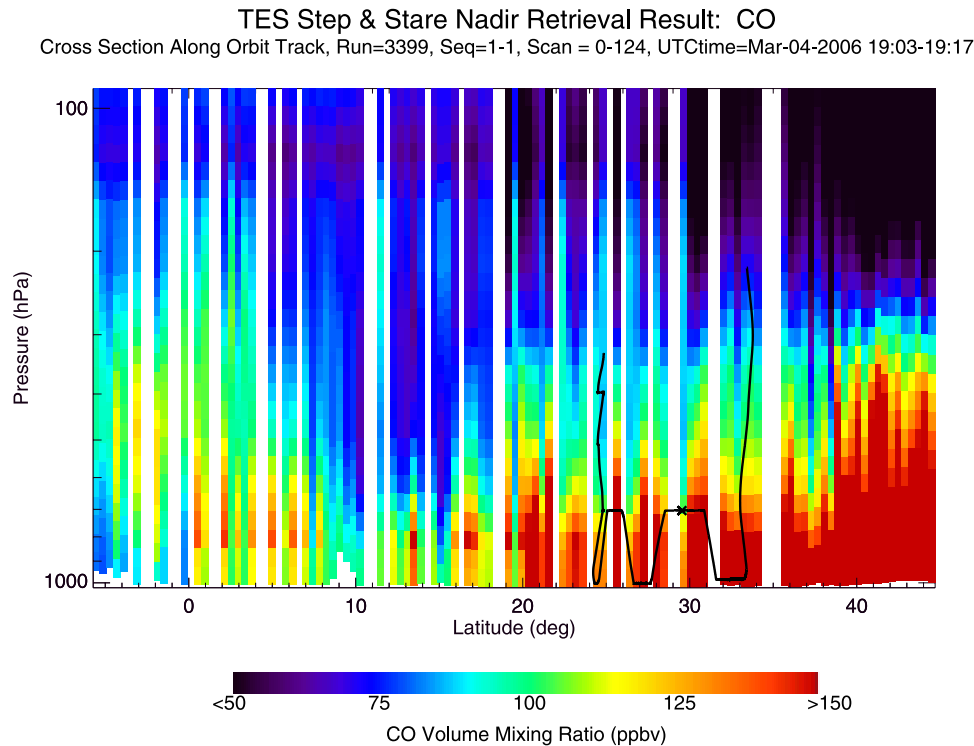
<sup>a</sup>Total number of DACOM CO profiles for comparisons in 5 flights: 3.

that includes three tunable diode lasers providing 4.7, 4.5 and 3.3  $\mu\text{m}$  radiation for accessing CO, N<sub>2</sub>O, and CH<sub>4</sub> absorption lines, respectively [Sachse *et al.*, 1987]. Calibration for all species is accomplished by periodically (every  $\sim 10$  min) flowing calibration gas through this instrument. By interpolating between these calibrations, slow drifts in instrument response are effectively suppressed yielding high precision values. Measurement accuracy is closely tied to the accuracy of reference gases obtained from NOAA/CMDL, Boulder, CO. Figure 7 shows DACOM CO measurements for the flight of 4 March 2006. A qualitative comparison between the TES CO latitude versus pressure (Figure 6) cross section and the DACOM measurements in the right bottom panel of Figure 7 shows reasonable agreement, e.g., high CO near the surface. Another way to illustrate this qualitative comparison is displaying the TES CO volume mixing ratios sampled along the DACOM flight

track. In this comparison, linear interpolations of CO values over pressure and latitude are performed. Figure 8 shows the sampled TES CO and the DACOM CO comparisons along the DC-8 flight track for the 4 March flight. As the DC-8 flew to higher and lower altitudes, changes in TES CO mixing ratios are similar to those measured by DACOM. The peak-to-peak changes in CO for TES are less than that of DACOM due to the vertical smoothing effect in nadir remote sensing retrievals, which is discussed in the next section.

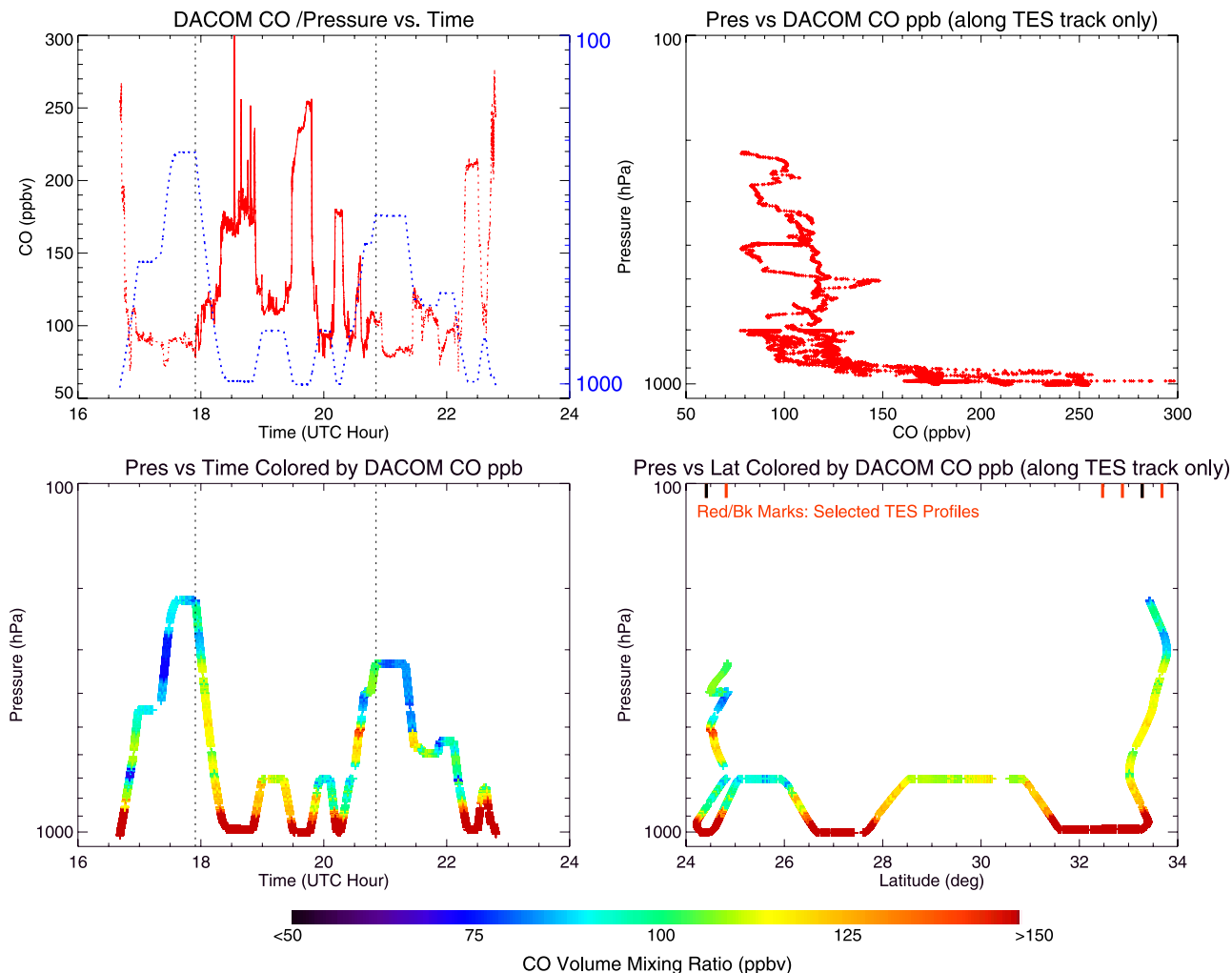
### 3. CO Profile Comparisons Between TES Nadir Retrievals and DACOM in Situ Measurements

[12] For each identified in situ CO profile, 1 to 3 TES CO profiles closest in distance to the DACOM locations are identified. As an example, the latitude marks in the right



**Figure 6.** Along satellite ground track latitude versus pressure curtain plot for TES CO retrievals taken in the Step & Stare observation run in 4 March 2006, near Houston (see Figure 1 for geolocations of the measurements). The DC-8 flight path pressure values are shown in black, and the symbol X indicates the location where TES and DC-8 coincide in time.

## DACOM CO Measurement Plots: Mar-04-2006



**Figure 7.** DACOM CO plots for the 4 March 2006 flight near Houston. Shown are the CO values as a function of time overlaid with the pressure of the DC-8 aircraft (top left), the CO values as a function of pressure for the aircraft path overlap with TES geolocations (top right), the CO values as a function of time and pressure (bottom left), and the CO values as a function of latitude and pressure (bottom right). This last panel can be compared to the TES curtain plot (Figure 6). The red/black marks at the top of the bottom right panel are the TES profile locations used to compare with the two DACOM CO profiles, respectively (black being the TES profile closest in distance to the averaged DACOM locations).

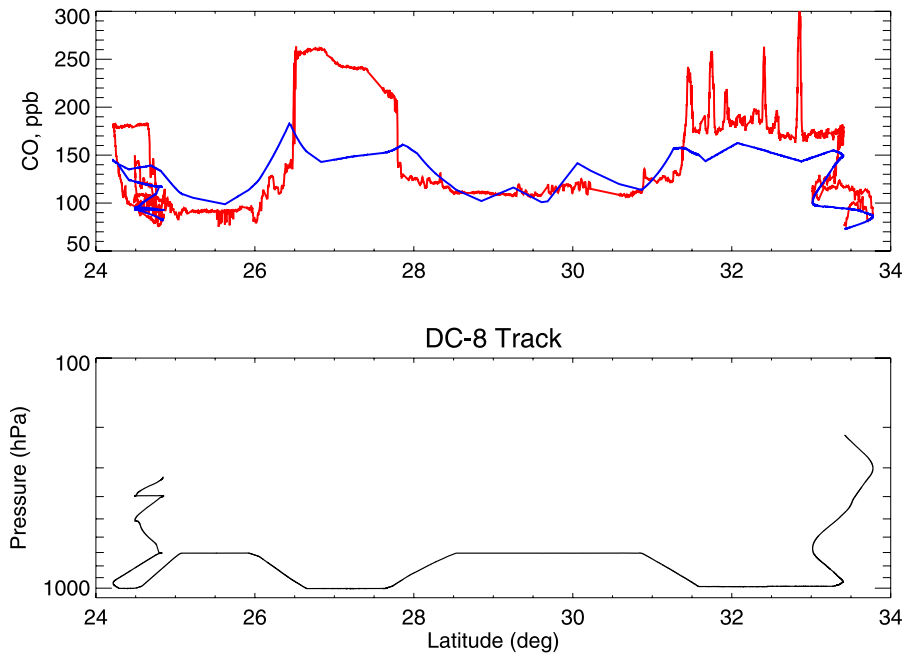
bottom panel of Figure 7 show the latitudes of the selected four TES CO profiles, where the black mark is the one closest to the averaged DACOM locations.

[13] Figures 9 and 10 illustrate steps taken in the TES-DACOM comparisons. Figure 9 is for the 4 March 2006 flight near Houston ( $\sim 50$  km and  $\sim 1$  hr between TES and DACOM profiles) and Figure 10 is for the 28 April 2006 flight near Hawaii ( $\sim 6$  km and 1.5–2 hr between TES and DACOM profiles). The top left panels show the original DACOM CO profile and the nearby TES profiles with retrieval errors. Although each DACOM CO profile derived from an aircraft vertical samplings is unique with layers of enhanced CO, the scales and vertical extends of the anomalous CO layers near Houston are generally small compared to those taken in Hawaii and Anchorage area. Furthermore, most of the elevated DACOM CO layers in the Houston area

are found near the surface while the elevated DACOM CO layers in Hawaii/Anchorage regions are mostly in the middle to upper troposphere. The comparisons in Figure 9 show that the TES and DACOM CO profiles have a similar shape, with the DACOM observations having more vertical structure (resolution). In Figure 10, the TES retrieved CO profile departed from the initial (a priori) profile toward the DACOM profile but does not compare well with the in situ profile in the lower and middle troposphere.

[14] The DACOM in situ measurement of CO has a vertical resolution much higher than that of TES and therefore direct comparisons between the two can be misleading. The remote sensing retrievals work by optimally combining the information from the spectral measurements and the a priori state of the CO profile using reasonable constraints. The retrieved species profile,  $x_{rets}$  can be related

DACOM CO (red) and TES CO Interpolated to DC-8 Track (blue): Mar-04-2006



**Figure 8.** TES-retrieved CO values are interpolated spatially to the DC-8 flying path (blue line) and compared to DACOM CO values measured by (red line) (top panel). The DC-8 pressures as a function of latitude are shown in the bottom panel.

to the true profile,  $x$ , by the following equation [Rodgers, 2000]:

$$x_{ret} = Ax + (I - A)x_a + \varepsilon \quad (1)$$

where  $A$  is the averaging kernel matrix,  $x_a$  is the a priori profile, and  $\varepsilon$  is the retrieval error due to random errors in the measurement and the systematic errors in the forward model. The averaging kernels are the key to understanding the satellite retrievals. The top right panels of Figures 9 and 10 show examples of TES averaging kernels at three selected pressure levels of lower, middle and upper troposphere. The TES-retrieved CO profile is the combination of vertically smoothed true profile (first term of equation (1)) and the a priori profile weighted by  $(I - A)$ , the second term of equation (1).

[15] For satellite data validation purposes, the high vertical resolution in situ measured CO profile with high precision can be treated as the true profile,  $x$ . For example, a DACOM CO profile measured during a downward spiral has over 1000 measurement points. The direct comparison of the TES-retrieved CO profile,  $x_{ret}$  to the DACOM CO profile,  $x$ , is then not meaningful due to their different vertical resolutions. In order to compare the in situ and the retrieved profiles properly, the in situ profile ( $x$ ) must be converted to  $x_{ret}$  via equation (1) and then compare this adjusted profile to the satellite retrieved profile [Rodgers and Connor, 2003; Emmons et al., 2004; Luo et al., 2007].

[16] It is important to point out that the in situ CO profile can only be used to evaluate the TES CO retrievals where the TES spectral measurements are sensitive to the pertur-

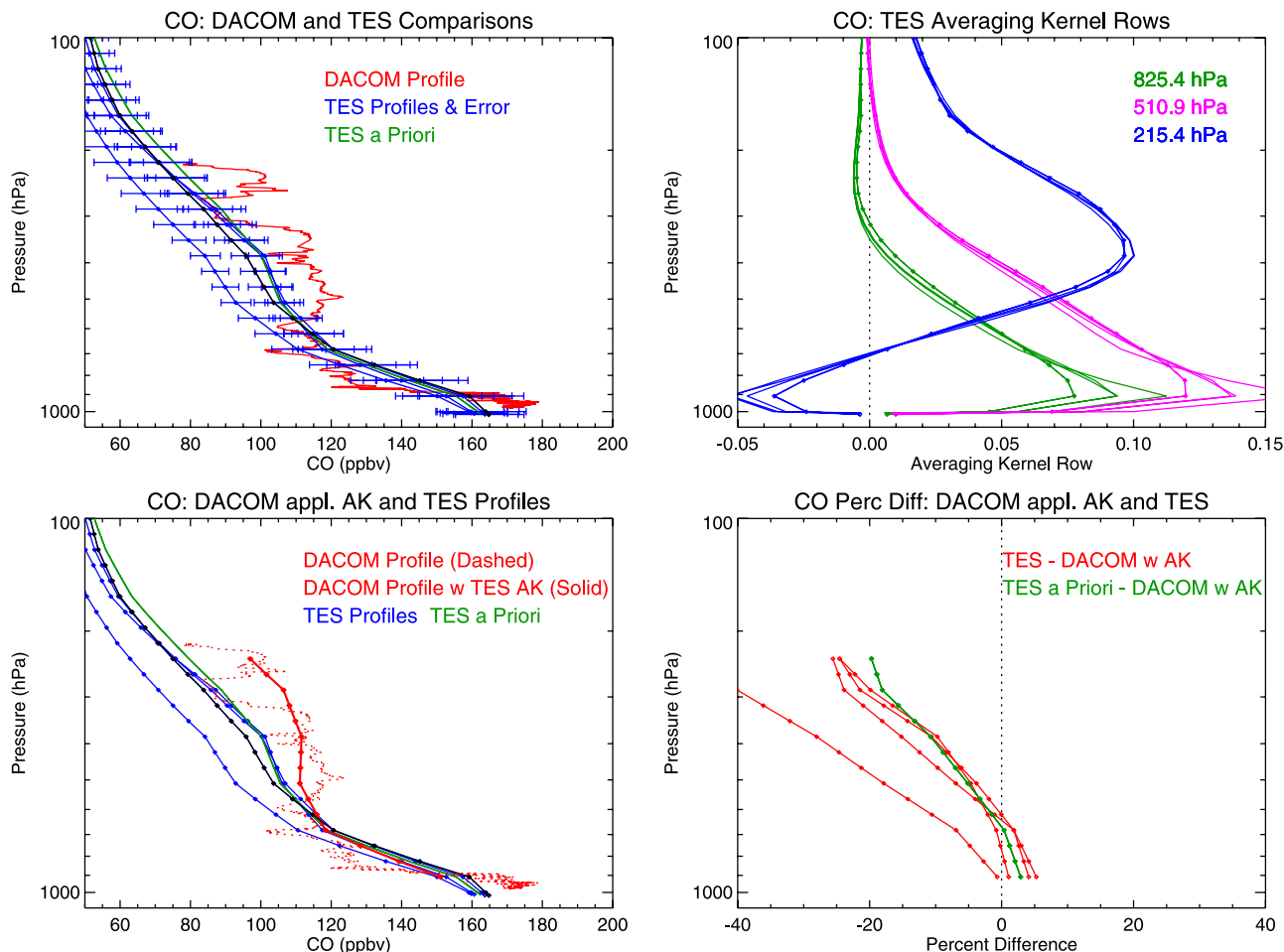
bations of the CO values. Profiles of CO retrieved by TES and all other infrared sounders differ from those from an ideal instrument in that they are smoothed by the a priori constraints applied in the retrieval process. The in situ CO measurement (viewed as the true CO profiles in satellite data validation) will not be able to justify the absolute TES CO retrieval values. In the processing of applying equation (1) to the in situ DACOM CO profiles, we add the influence of the TES a priori constraints. When we compare these adjusted in situ CO profiles to the TES retrievals, the effect of a priori is canceled out.

[17] The bottom two panels of Figure 9 show adjusted DACOM CO profiles compared to the TES CO profiles and their differences for the 4 March 2006 flight. Since the DACOM profile only covers below about 200 hPa, we use shifted TES a priori profile to extend the DACOM profile to above this pressure level before applying the TES averaging kernel to it in equation (1). The TES CO a priori profile and its comparison to the DACOM profile are also shown in Figure 9 as reference. In this comparison, TES CO profiles show a larger vertical decrease with altitude than the DACOM profile.

[18] In the case of Figure 10 (28 April, near Hawaii), the TES CO retrievals do not show the layer of enhanced CO in 500–250 hPa that DACOM detected, which is also an evident in the adjusted DACOM CO profile. Studies show that Asian air pollution outflow and its transpacific transport are characterized by sporadic events of high CO in the central and northern pacific in spring [Heald et al., 2003]. This characteristic is seen in TES CO global survey observations as high variability between adjacent profiles along



## TES & DACOM CO Comparisons (1): Mar-04-2006



**Figure 9.** An example of TES and DACOM CO profile comparisons. The CO profiles were taken near Houston, 4 March 2006. The DACOM CO values (red in top and bottom left panels) were sampled in the spiral down flight portion (Figure 3, profile 1). Four TES CO profiles near the DACOM profile are selected for comparisons (blue/black in top and bottom left panels, the black profile being the one closest to the averaged DACOM locations in distance). The TES averaging kernels (AK) corresponding to three sample pressures are plotted in top right panel. The bottom right panel shows the percent difference in CO profiles between TES and DACOM, where the DACOM profile is the one after applying TES AK and the a priori profile.

an orbit [Rinsland *et al.*, 2006]. These sporadic events make validation of the CO profile more difficult, compared to those from regions with more homogeneous CO.

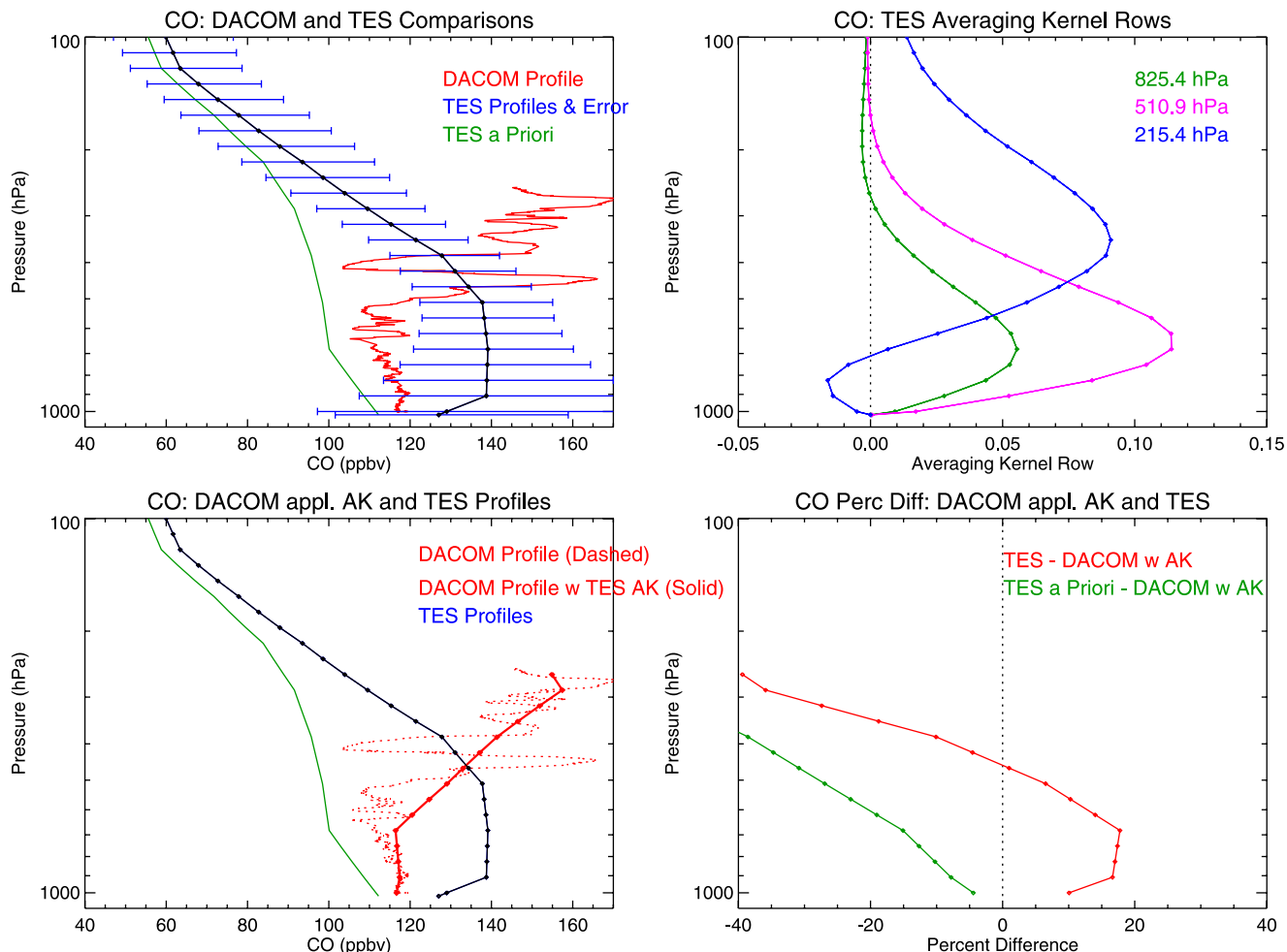
### 4. Comparison Statistics for the Three INTEX-B Areas

[19] The comparison statistics between TES CO retrievals and DACOM measurements are compiled separately for the three INTEX-B time periods. Houston, Hawaii, and Anchorage are all affected by different CO production sources and transport mechanisms. During the spring season, March to May, the tropics biomass burning sources of CO in South America and Africa are at their annual minimum so their influence to the INTEX-B observation regions is negligible. TES and MOPITT CO global distributions show higher CO in northern high latitudes with identifiable sources over

China [Clerbaux *et al.*, 2004; Rinsland *et al.*, 2006; Luo and Richards, 2006]. By comparison, the CO values in Houston area are more uniform and smaller in magnitude. Therefore the measurements of CO made by TES and DACOM reflect the different characteristics of the three regions.

[20] The averaging kernels for a given satellite retrieved profile are the key for understanding the physics in the process as illustrated in Figures 9 and 10 for the two example cases. They describe how sensitive that the retrieved value at a given pressure level to the true species values at all levels. The areas of the averaging kernels represent the fractions of the contributions of the true profile to the retrievals as a function of pressure [Rodgers, 2000]. Figure 11 shows the profiles of the TES CO averaging kernel areas in Houston, Hawaii, and Anchorage regions, respectively. TES CO retrieved profiles are most sensitive in the pressure regions below 200 hPa and above ~700 hPa for

## TES & DACOM CO Comparisons (1): Apr-28-2006



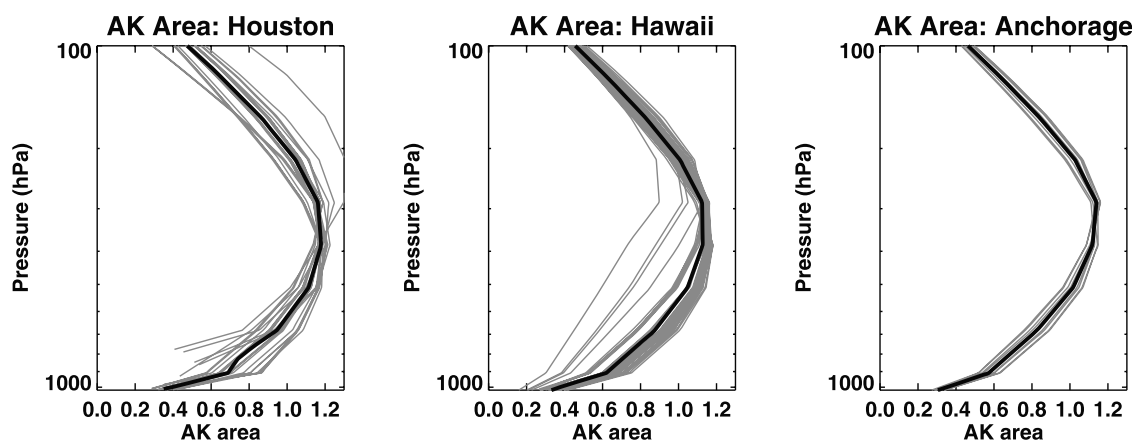
**Figure 10.** Similar to Figure 9, another example of TES and DACOM CO profile comparisons. The TES and DACOM CO profiles were taken near Hawaii, 28 April 2006.

the Houston region and 600–550 hPa in Hawaii and Anchorage regions. TES CO profiles are less sensitive to the true state in the lower and upper troposphere, and the retrievals in these pressure ranges are dominated by the a priori.

[21] Figure 12 shows the summary comparisons between TES and DACOM CO profiles near Houston, March 2006. The correlation coefficient for all selected TES and DACOM CO profiles is 0.87, and improves to 0.94 when only one TES CO profile closest to the averaged DACOM location is considered for a given DACOM CO profile. The agreement between TES and DACOM CO profiles is within 10% in the lower and middle troposphere with TES being lower in the middle troposphere. The difference between TES and DACOM CO observations is smaller than the variability of both the TES and DACOM measurements for this region. The standard deviations of TES and DACOM CO data are 10–15% and 15–20%, respectively. The standard deviations of TES CO retrievals are comparable with the estimated total errors in TES retrievals. The TES CO observation errors, including errors due to measurement noise and the systematic errors (the last term in equation (1))

should be the error associated with TES and DACOM CO data comparisons here if the variability due to offsets in time and location are ignored [Rodgers and Connor, 2003]. The TES observation error is estimated to be 5–10% in the low latitudes to midlatitudes [Rinsland et al., 2006].

[22] Figure 13 shows the summary comparisons between TES and DACOM CO profiles near Hawaii, April to May 2006. The data correlation coefficient is only 0.23 (not shown). The DACOM CO profiles in this area showed larger variability (see the example in Figure 10) compared to those taken in Houston area. In most flights, DACOM CO profiles detected plumes or enhanced CO layers in the middle troposphere (daily report in <http://www.espo.nasa.gov/intex-b/>). In these situations the CO concentrations vary strongly with location and time; thus a slight mismatch between the TES and DACOM CO profiles could result in substantial differences. The selected TES retrieved CO profiles do not capture the broad layers of enhanced CO in the adjusted DACOM profiles, but most of them have moved away from the initial guess to either match the shapes or the magnitudes of the in situ profiles to some degree.



**Figure 11.** The area of the averaging kernels as a function of pressure for the selected TES CO profiles used to compare with DACOM in situ profiles near Houston, Hawaii, and Anchorage regions. The individual profiles are in light gray and the averaged profiles are in black for the three regions, respectively.

[23] Figure 14 shows the summary comparisons between TES and DACOM CO profiles near Anchorage, May 2006. The average of the three adjusted DACOM CO profiles shows a huge enhancement of CO in the middle and upper troposphere, dominated by the observations on 7 May 2006 (<http://www.espo.nasa.gov/intex-b/>). This layer of enhanced CO observed in the DACOM measurement is not captured by the TES retrievals sampled 300 km away. For the 9 May flight in which the DACOM spiral CO profile was within a few tens of kilometers from the TES profiles, but 1.5–2.0 hours apart, the three TES CO profiles still disagree with that of DACOM by  $\pm 35\%$ . The meteorological conditions (<http://www.espo.nasa.gov/intex-b/>) suggest that the area is part of the transpacific pathway for the pollution events originated in the north-east China, hence comparisons between TES and the in situ measurements of CO are not expected to be in good agreement.

[24] In the portions of a given profile where TES measurements have low sensitivity to the species profile, the agreement between TES retrievals and the adjusted in situ measurements is nearly perfect but is meaningless. For example, in all comparisons in the three areas, TES and DACOM CO values agree much better in the lower troposphere than the middle troposphere (Figures 12–14). This is because TES retrievals and the adjusted DACOM CO profiles near the surface are both dominated by the a priori assumptions (see Figure 11) due to the low sensitivity of TES measurements to this portion of the atmosphere.

## 5. Conclusions

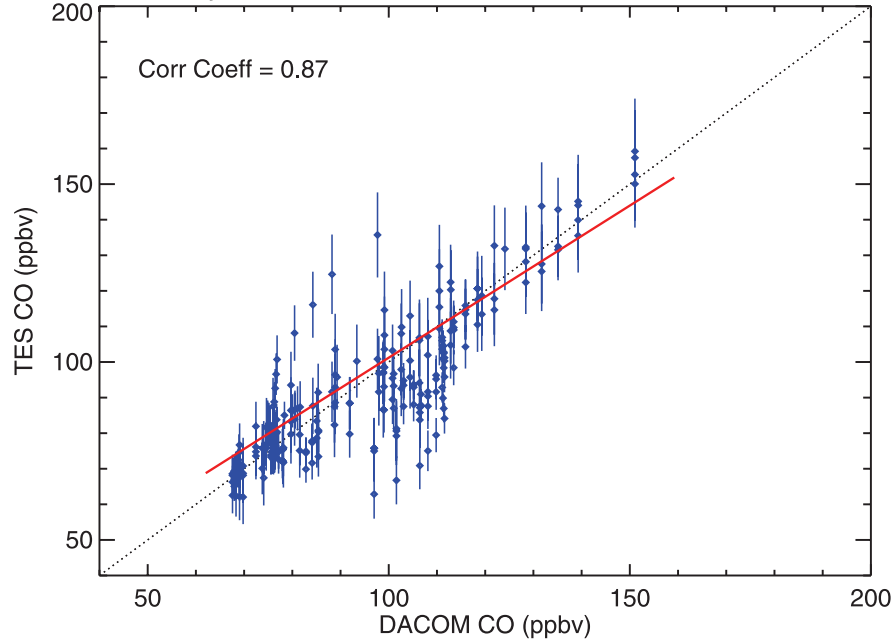
[25] We have presented validation of TES CO retrievals with the in situ CO measurements taken by the DACOM instrument on the DC-8 during the INTEx-B aircraft campaign, in March to May 2006. Following proper procedures for comparisons between remote sensing retrievals and in situ measurements, we adjusted DACOM CO profiles by the TES averaging kernels and the a priori profiles from the TES CO retrievals. The comparisons between TES and the adjusted DACOM CO profiles for

the three INTEx-B regions, near Houston, Hawaii, and Anchorage, are representative examples of different atmospheric conditions. In the area where the background level of CO in the atmosphere dominates with relatively small contributions from regional pollution and long range transport (near Houston), the TES and the adjusted DACOM CO profiles show similar shapes and the correlation coefficient has a high value of 0.87. In the area where pollution transport dominates the CO profiles, e.g., near Hawaii and Anchorage, TES and the adjusted DACOM CO profiles do not agree well and the DACOM in situ CO measurements show enhanced CO layers in middle or lower troposphere sporadically. It is therefore difficult to use such data for satellite profile validation, due to highly restrictive requirements for time and location coincidences.

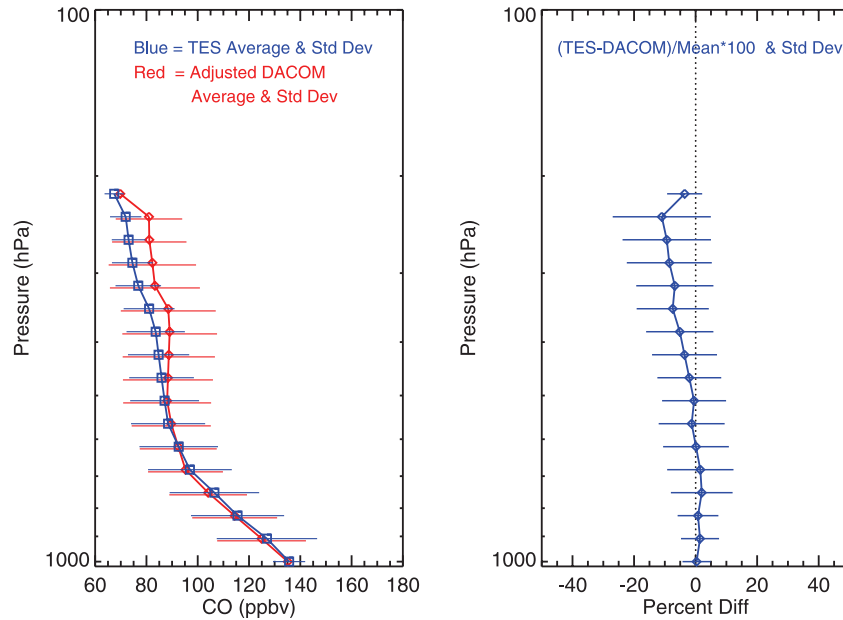
[26] It should be noted that the differences reported here cannot be used to evaluate the absolute accuracy of the satellite retrieved profiles. The absolute error in the retrieved profile necessarily include additional uncertainties such as bias in TES radiances [Shephard *et al.*, 2007], errors in the spectroscopic parameters adopted for CO, systematic errors in the retrieval (e.g., clouds, temperature, etc.), and a priori assumptions. We have therefore focused on understanding the bias of TES measurements with respect to in situ profiles where the smoothing error is explicitly removed [Rodgers, 2000, Rodgers and Connor, 2003]. When using the methods described in this and other papers [e.g., Emmons *et al.*, 2004; Worden *et al.*, 2007; Luo *et al.*, 2007], the effect of the a priori profile is removed when differencing the TES retrieval and the adjusted in situ profile. In the portions of the vertical profile where TES has very little sensitivity and therefore retrieval errors are dominated by the smoothing error, the comparison is close to zero [also see Nassar *et al.*, 2007; Lopez *et al.*, submitted manuscript, 2007].

[27] In addition to the past and present TES CO validation activities reported in this Aura validation special section, several sources of CO data have been considered for inter-comparisons with TES CO retrievals in the near future. These data include CO profile data from Aqua/

CO: TES vs adjusted DACOM for INTEX-B near Houston, March 2006



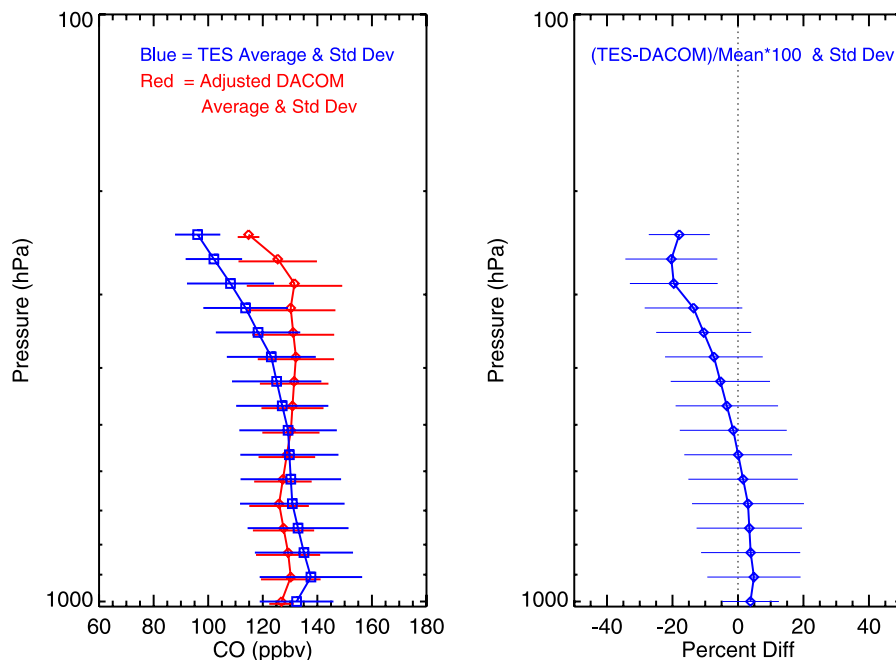
CO: TES and Adjusted DACOM Comparison for INTEX-B near Houston, March 2006



**Figure 12.** Summary plots for TES and DACOM CO profile comparisons during INTEX-B near Houston, March 2006. The top panel shows the correlation plot of TES with retrieval error versus DACOM CO profiles, where DACOM CO profiles are those with TES AK and a priori profiles applied (see the example in Figure 9). The bottom left panel shows the averaged CO profiles of TES and DACOM with standard deviations (vertically shifted for distinguishing) from the two measurement sets. The bottom right panel shows the averaged percent differences between TES and DACOM CO profiles with the standard deviation.



## CO: TES and Adjusted DACOM Comparison for INTEX-B near Hawaii, April 2006

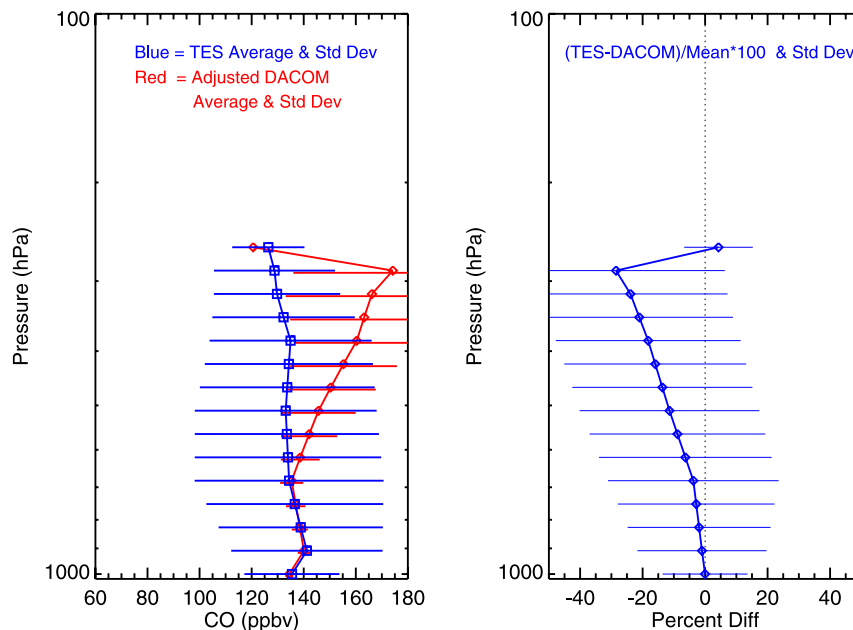


**Figure 13.** Summary plots for TES and DACOM CO profile comparisons during INTEX-B near Hawaii, April to May 2006. All the colored symbols and lines are defined the same as in Figure 12.

AIRS, MLS CO retrievals in the upper troposphere, the upcoming IASI data set, the long-term MOZAIC measurements, MOPITT data, solar occultation measurements from the Atmospheric Chemistry Experiment (ACE) Fourier transform spectrometer [Bernath *et al.*, 2005], and ground-based observations (e.g., Network for the Detection

of Atmospheric Composition Change (NDAAC) data from a global network of surface sites with longer time coverage). The additional measurement sets will help validate and confirm the systematic biases in TES tropospheric CO profile relative to the in situ measurements concluded from this study and Lopez *et al.* (submitted manuscript, 2007) in

## CO: TES and Adjusted DACOM Comparison for INTEX-B near Anchorage, May 2006



**Figure 14.** Summary plots for TES and DACOM CO profile comparisons during INTEX-B near Anchorage, May 2006. The colored symbols and lines are defined the same as in Figure 12.

the midlatitudes and Lopez et al. (submitted manuscript, 2007) in the tropics.

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